

Effect of understory management on phenological responses of eastern black walnut on an alluvial Arkansas soil

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Abstract Black walnut (*Juglans nigra* L.) is commonly grown in agroforestry practices for nuts and/or timber with little knowledge of how understory herbage management might affect tree phenology. We compared black walnut plant type (variety and wild-type) for phenological response in date of budburst, leaf area index (LAI), quantum yield of photosystem II (Fv/Fm), radial stem growth, and total chlorophyll concentration in response to understory herbage N fertilization and herbage suppression in an agroforestry practice on an alluvial soil. Herbage

treatments generally had little impact on phenological responses, although N fertilization increased herbage yield that delayed budburst. Radial stem growth commenced at about budburst (mid-April) and virtually ceased in late October, about 30 days before leaf drop. Early-season radial stem growth was greater for the wild-type than the variety, while the variety had more rapid late-season growth. The wild-type had consistently greater LAI than the variety at any given day-of-year (DOY), and usually had greater LAI than the variety regardless of herbage treatment. Leaves of both plant types maintained a high Fv/Fm during most of the growing season, but total chlorophyll concentration decreased across DOY regardless of plant type. N fertilizer should be applied with understory herbage suppression to avoid delay of budburst. Further study is needed of phenological responses during longer growth periods, or as affected by latitude, soil water, and soil fertility.

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Introduction

Black walnut (*Juglans nigra* L.), is one of the most highly valued of native, North American hardwoods for nut and timber production (Coggeshall 2011; Harlow and Harrar 1969), and for alley cropping agroforestry practices in the U.S. (Garrett and

McGraw 2000), Europe (Nicolescu 1998), and Asia (Rehnus et al. 2013). Black walnut growth is affected by soil type and depth to a restrictive soil layer (Geyer and Ponder 2013). Best growth occurs on deep, fertile, moist soils of alluvial origin, and growth is poor on sub-optimal sites (Geyer and Ponder 2013; Harlow and Harrar 1969). Black walnut has been successfully established on reclaimed, albeit fertile, mine land (Andersen et al. 1989). As with most hardwood species, control of competing herbaceous vegetation is very important during seedling establishment, particularly during the first 4 years of establishment (Andersen et al. 1989). The photosynthetic apparatus of black walnut is especially prone to drought stress, compromising its ability to thrive on xeric sites (Ni and Pallardy 1991; Parker and Pallardy 1991). Suppression of herbaceous vegetation within the tree root zone could benefit tree growth.

Varieties developed for nut production have been tested for traits such as budbreak, flowering, fruit quality (Warmund and Coggeshall 2005, 2010), and genetic diversity (Coggeshall and Woeste 2010) and, because of selection, usually have better nut quality, nut yield, and earlier flowering than the unselected wild-type (Brauer et al. 2009, 2010). Nut varieties are managed for a short trunk, wide-spreading branches, and a full canopy to facilitate and optimize nut production (Reid et al. 2009). As such, resulting stands typically have such poor tree form and stem damage from orchard machinery that they have negligible timber value (Ares and Brauer 2004). Conversely, most domestic nut production actually comes from wild-type trees and timber quality usually is better from tall, straight, minimally-branched, wild-type trees from mixed hardwood stands (Ares and Brauer 2004; Reid et al. 2009). Thus, growers should decide a priori if a given stand is to be managed for either nuts or timber.

For our purposes, phenology describes the periodic change in growth responses beginning with budburst and terminating at leaf drop. Genetic responses in growth phenology have been reported for black walnut (Augspurger 2009; Lucier and Hinckley 1982), and English walnut, *Juglans regia* L. (Aletà et al. 2009; Pope et al. 2013), but it is not known if plant type influences growth phenology. Effects of management practices on phenology have not been intensively studied, but phenology of pecan [*Carya illinoiensis* (Wangenh.) K. Koch] and white oak (*Quercus alba* L.) grown under intensive management practices was generally not responsive to N fertilization (Burner et al. 2014).

Our objective was to compare black walnut plant type (variety and wild-type) for phenological response in date of budburst, leaf area index (LAI), quantum yield of photosystem II (Fv/Fm), radial stem growth, and total chlorophyll concentration in response to understory herbage N fertilization and herbage suppression in an agroforestry practice on an alluvial soil.

Materials and methods

Experimental site and cultural practices

The experimental site was at 35.09°N, 93.97°W, near Booneville, Arkansas, 139 m a.s.l., 0.1 % slope on a stream terrace. Soil was a Spadra silt loam (fine-loamy, siliceous, active, thermic typic Hapludult), a deep (>1.8 m to bedrock) soil formed in loamy alluvium (USDA 2012). Soil cores conducted in August 2002 indicated that the depth to the shale bedrock varied between 1.8 and 2.2 m. Adjacent to the planting site was a creek that flowed most months. The creek adjacent to planting site contained numerous pools permitting lateral water movement into the subsoil beneath the walnut planting.

Black walnut was indigenous to an adjacent riparian area which was allowed to reforest naturally about 40 years prior, confirming its adaptability (USDA 2012). The site, a former pasture primarily composed of tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., ex *Festuca arundinacea* Schreb.] and bermudagrass [*Cynodon dactylon* (L.) Pers.], flooded periodically but usually was free of standing water by 1-day post-flood. Plantation establishment was described by Brauer et al. (2010).

The test included two types of germplasm, variety and wild-type (Table 1). One-yr-old seedlings of walnut were initially grown in 10 L pots using a root pruning technology (patent number 7308775) developed to improve tree survival and initial growth (Lovelace 1998; Forrest Keeling Nursery, Elsberry, Missouri). Trees (1–1.2 m in height) were transplanted in augered holes (30 cm diameter and 60 cm-deep) in January 2003 and 2004. Spacing was 3.7 m within rows and 7.3 m between rows, or 370 trees ha^{-1} , in a design emulating a mixed hardwood alley cropping agroforestry practice (Garrett and McGraw 2000).

Table 1 Tree type, graft source, number of trees, and planting date for black walnut grown near Booneville, Arkansas

Type	Scion	Root	Trees (no.)	Planting date
Variety ¹	Emma K	Kwik Krop	2	2003
	Emma K	Not grafted	2	2004
	Kwik Krop	Kwik Krop	2	2003
	Sauber	Kwik Krop	3	2003
	Sauber	Not grafted	1	2004
	Spark's 127	Not grafted	5	2004
	Sparrow	Kwik Krop	3	2003
Wild-type	Unimproved	Not grafted	24	2003

¹ Nut variety

A 1 m² weed mat was attached to the soil surface under each tree. Trees were periodically irrigated to foster establishment during 2003–2007. Competing vegetation within 1 m radius of the tree stem was controlled by annual applications of glyphosate [*N*-(phosphonomethyl) glycine] (Andersen et al. 1989; Houx et al. 2013; Schlesinger and Funk 1977; Turner 2006), typically applied at 1.06 kg a.i. ha⁻¹ in May, mid-June, and early August. In 2003–2007, 20 g Osmocote (ScottsMiracle-Gro, Marysville, Ohio), a commercial, slow release fertilizer having an analysis of 14-14-14 (percent N, P₂O₅, and K₂O, respectively), was split-applied (early-May and mid-July) to a 1 m² area to supply 56, 43, and 47 kg ha⁻¹ tree⁻¹ year⁻¹ of N, P, and K, respectively. Dormant trees were pruned as needed during winter to promote a single leader.

Chemical vegetation control ceased in 2008, but weed barriers remained in place. Trees were not fertilized in 2009–2010. Tops of some trees were broken during two storms in June, 2008 when straight line wind gust exceeded 130 km h⁻¹. Severely damaged trees were removed in July, 2008. Varietal trees were more likely to be severely damaged, possibly because of a greater nut load at the time of the storms.

Weed barriers were removed and trees were thinned in December 2010 to minimize tree-tree competition. Post-thinning spacing was nominally 7.4 m within rows and 7.3 m between rows, or 185 trees ha⁻¹. Thinning was consistent with recommended stocking-tree size practices for timber (Balandier and Dupraz 1999; Schlesinger and Funk 1977), but overstocked by ≥54 % for a nut orchard (Coggeshall 2011; Reid et al. 2009). Examination of stumps of thinned trees

indicated a growth rate of basal stem diameter of about 1 cm year⁻¹, demonstrating this was a good site for black walnut (Balandier and Dupraz 1999). Tree canopies did not overlap during the test. Fall webworm (*Hyphantria cunea* Drury), a walnut pest, was controlled by annual (June) applications of tebufenozide [3,5-dimethylbenzoic acid 1-(1,1-dimethylethyl)-2-(4-ethylbenzoyl) hydrazide] insecticide (Dow Agro-Sciences, Indianapolis, Indiana) applied to the tree canopy at 0.40 mL L⁻¹ a.i. with an air-blast sprayer.

Pre-test (February 2011) topsoil (0–15 cm depth) pH was 5.7; Mehlich-3 (Mehlich 1984) extractable P (28 mg kg⁻¹) and K (110 mg kg⁻¹) were at medium levels (Espinoza et al. 2007) according to analyses by the University of Arkansas Diagnostic Laboratory (Fayetteville). Thus, no supplemental P and K fertilizer was applied.

Environmental monitoring

Air temperature and rainfall were used to characterize climatic conditions from April–October 2011–2012. Data were obtained from an electronic weather station located 2.7 km southwest of the experimental area. Air temperature was measured with a thermocouple located 1.5 m above ground, and rainfall was recorded at 1.5 m above ground with a self-tipping gauge. Data were expressed as mean monthly air temperature and total monthly rainfall. Air temperature and rainfall were compared to the long-term mean (1971–2000) from a weather station located 6.8 km northeast of the experimental site (NOAA 2002).

Volumetric soil water was measured using time domain reflectrometry (TDR, MESA Systems Co., Medfield, Massachusetts), calibrated for mineral soil, to characterize soil water depletion across the growing season. Access tubes 1 m long were permanently installed 1.5 m from the tree stem under six random trees per type. Soil water was measured about every 8 days (2011) and 10 days (2012) at 10, 35, and 70 cm depths from April to October.

Experimental treatments

Three levels of herbage suppression treatments were applied to the tree understory beginning in mid-May 2011: Control (no herbage suppression), mow (herbage maintained at about 8 cm stubble height), and herbicide (glyphosate, same rate as above, applied in

mid-June and thereafter as needed throughout the growing season to maintain a minimally vegetated understory). Treatments were applied to an area of 2.5 m radius under each tree (within the drip line), based on mean canopy radius. Most of the herbage being suppressed consisted of grass monocot species remaining from the previous perennial pasture as discussed above, primarily bermudagrass [*Cynodon dactylon* (L.) Pers.] and tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., ex *Festuca arundinacea* Schreb.]. Minor grass species also present included: yellow nutsedge (*Cyperus esculentus*), cheat grass (*Bromus secalinus*), foxtail (*Setaria spp.*), and annual ryegrass (*Lolium multiflorum*). Although not abundant, the following dicot species were present: white clover (*Trifolium repens* L.); arrowleaf clover (*Trifolium vesiculosum*), buttercup (*Ranunculus spp.*), ironweed (*Vernonia altissima*), blackberry (*Rubus fruticosus*), goldenrod (*Solidago L.*), honeysuckle (*Lonicera spp.*), horse nettle (*Solanum carolinense*), maypop (*Passiflora incarnata*), smartweed (*Polygonum*), curly dock (*Rumex crispus*), honey locust (*Gleditsia triacanthos*), black locust (*Robinia pseudoacacia*), common ragweed (*Ambrosia artemisiifolia*) and lanceleaf ragweed (*Ambrosia bidentata*).

Two levels of N fertilization were applied to the same understory area as herbage suppression: 0 and 100 kg ha⁻¹ year⁻¹ per tree applied as granular commercial NH₄NO₃ fertilizer having an analysis of 27-0-0 (percent N, P₂O₅, and K₂O, respectively). N fertilizer was broadcast applied to the soil surface in two splits: one-half in late-April 2011 and one-half 6 weeks later. There were six trees per replication, with three replications of treatments for the variety and four replications for the wild-type. Treatments were reapplied to the same trees in 2012 as in 2011.

Soil and foliar analyses

Soil was sampled from the drip line area under each tree in February 2011 and January 2012 using a truck-mounted soil sampler with a soil tube 5.7 cm diameter by 1.9 m long (Giddings Machine Co., Windsor, CO). A soil core was collected under each tree and sectioned into samples 0–10, 10–30, 30–60, and 60–90 cm depth. A soil core was similarly collected in July 2011 and July 2012, but due to hard, dry soil conditions only samples at 0–10 cm depth could be collected. Samples were air-dried and ground in a mortar to pass a 1.4 mm

screen. Soil P was extracted in Mehlich-3 (Mehlich 1984) and analyzed using inductively coupled plasma spectrometry (ICP) (Varian VistaPro, Santa Clara, California).

Yield of understory herbage was characterized by harvesting a 0.1 m² quadrat five times in 2011 (11 June, 18 July, 23 August, 30 September, and 1 November), and three times in 2012 (1 June, 18 July, and 12 September) from the control treatment. Personnel exigencies required that sampling be terminated in October 2012. Samples were dried at 60 °C to calculate mass (kg ha⁻¹), ground to pass a 1 mm screen, and stored at –20 °C prior to combustion N analysis using an Elementar Vario Max C/N analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Foliar P was determined using inductively coupled plasma spectrometry (ICP) (Varian VistaPro, Santa Clara, California) following HNO₃ digestion (Havlin and Soltanpour 1980).

A pair of axillary, non-terminal leaflets were collected in July 2011–2012 from each of 25 leaves around the periphery of the tree canopy, dried, ground, and stored prior to combustion N analysis (as described above). A tissue sample of known N concentration (*Populus deltoides* Bartr. ex Marsh., LECO, Inc., St. Joseph, Michigan) was analyzed at the beginning, end, and at every 20th sample to confirm operation of the combustion analyzer. Foliar P (g kg⁻¹) was determined using ICP following HNO₃ digestion (Havlin and Soltanpour 1980).

Tree growth measurements

Diameter at 1.4 m above soil surface (dbh) using a diameter tape (d-tape), and height using a clinometer, were measured annually in fall-winter 2010 (pre-test) and 2011 when trees were dormant (after leaf drop). Trees were not dormant when measured in September 2012. A hand-crafted, stainless steel band dendrometer (Keeland and Young 2012) was installed around each tree stem at about 1 m above soil surface in January 2011. Change in radial stem circumference (mm) was recorded at about 2-week intervals from March through October 2011–2012 (only positive changes could be measured) using a caliper, and converted from circumference to diameter. Radial stem growth was divided by number of days since previous reading, typically 14, to calculate growth rate (mm day⁻¹). Annual radial stem growth (mm) was

summed across measurement dates and compared to annual dbh growth.

Budburst was the date at which green leaf tissue was first visible in the swelling buds (Foss and Rieske 2003; Polgar and Primack 2011). Date of budburst was monitored at 2-day intervals from March to April 2011 and 2012.

Leaf area index (LAI) was measured at 2-week intervals using a plant canopy digital imager (CI-110, software version 3.0.2.0, CID, Inc., Camas, Washington). LAI was measured at about sunrise on 17 dates in 2011 [11 July, day-of-year (DOY) 192, to 28 October 2011, DOY 301] and 2012 (2 June, DOY 154, to 25 September 2012, DOY 269) at two arbitrary positions under the canopy, roughly 180° apart, at about 1.2 m above soil surface and 40 cm from the tree stem. LAI was adjusted by subtracting that measured after leaf drop (15 December 2011, DOY 349) according to (Kucharik et al. 1998), and the two measurements were averaged for each tree on each sampling date.

Maximum photosynthetic quantum yield of photosystem II (F_v/F_m) was measured with a Fluorpen FP100, Qubit Systems Inc., Kingston Ontario, Canada at 2-week intervals from 7 June to 12 October 2012 ($n = 13$ dates). Measurements were conducted at pre-dawn on two healthy, dark-adapted leaves per tree on the periphery of the tree canopy, and averaged for each tree per sampling date. Readings were confined to green-colored regions of the leaf lamina.

A leaf disk measuring 6.3 mm in diameter was collected at mid-day from the green-colored lamina of each of three fully-illuminated leaves per tree (3 disks per tree) at 2-week intervals from July through October 2011–2012. Samples were immediately placed in an amber glass vial containing 5 mL of 100 % ethanol. After 7-day incubation at 5 °C, absorbance of the extract was read at 649 and 665 nm (Spectronic 20, ThermoFisher Scientific Inc., Pittsburgh, Pennsylvania), and converted to chlorophyll *a* and *b* concentration in $\mu\text{g cm}^{-2}$; chlorophyll *a* and *b* concentrations were summed to provide total chlorophyll concentration (Dillenburg et al. 1995; Knudson et al. 1977).

Experimental design and statistical analyses

The experiment was a split plot design with type (variety and wild-type) as the whole plot, because the variety and wild-type were planted at north and south areas of the field, respectively. There was a factorial

arrangement of understory treatments: three herbage suppression treatments and two N rates, assigned randomly within whole plots. Genotypes within type were considered random.

Analysis of variance (anova) was conducted with a mixed linear model procedure, Proc Mixed (Littell et al. 1996; SAS Inst. 2002). Fixed effects in anova were year, type, herbage treatment, N-rate, and their interactions. Genotype within type was the repeated measure with a first-order autoregressive covariance structure and restricted maximum likelihood estimation method (Littell et al. 1996; SAS Inst. 2002). Random effects were replication and its interactions with fixed effects. Anova for soil water used year, DOY, depth, and their interactions as fixed effects. Pre-test (2010) growth measurements were used as covariates for anova of dbh and height. Least squares means were compared at $P \leq 0.05$ using the Tukey honest significant difference (HSD) when main effects or interactions differed at $P \leq 0.05$. SigmaPlot 12.0 (Systat Software, Inc., San Jose, California) or Proc Reg (SAS Inst. 2002) were used to examine temporal responses. Use of the term “significant” implies a $P \leq 0.05$ except as noted otherwise. Where appropriate, Proc Reg procedure (SAS Inst. 2002) was used to examine temporal responses and those trend values were identified in the figures as predicted values. Proc Reg was also used to determine the strength of the predictive power of these temporal responses using R^2 , and those values are included the figures.

Results and discussion

Environmental conditions

In 2011, air temperatures were about normal during April–May (NOAA 2002), above normal during June–August, and below normal during September–October (Fig. 1a). Air temperatures during 2012 were consistently at or above normal. Rainfall in 2011 equaled or exceeded the long-term mean for all months except June–July, while rainfall in 2012 was consistently below normal except in September (Fig. 1b).

There was a significant depth by DOY interaction in soil water, with differing seasonal depletion responses at 10 cm depth compared to those at 35 and 70 cm depths (Fig. 2). At 10 cm depth, minimum predicted soil water

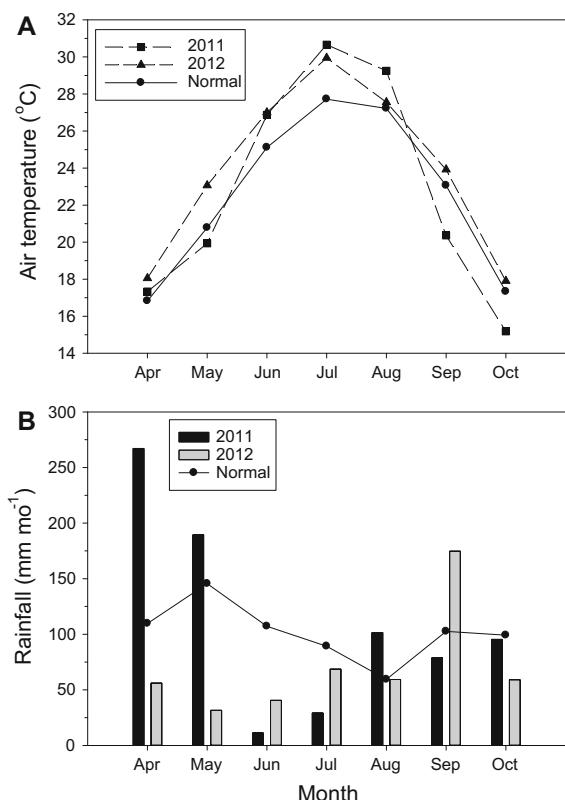


Fig. 1 Mean monthly air temperature (a) and total monthly rainfall (b) in 2011 and 2012 near Booneville, Arkansas. Normal air temperature and rainfall were from NOAA (2002)

concentration was 183.7 g kg^{-1} at DOY 208 (27 July), a decrease of $9.0 \text{ g kg}^{-1} \text{ day}^{-1}$ from DOY 98 (8 April). Compared to that at 10 cm depth, minimum predicted soil water concentrations tended to be lower and occur later at 35 cm (159.2 g kg^{-1} at DOY 238) or 70 cm depths (176.0 g kg^{-1} at DOY 258). The early-season rate of decrease in predicted soil water concentration also tended to be slower at 35 cm ($5.2 \text{ g kg}^{-1} \text{ day}^{-1}$) and 70 cm depths ($3.7 \text{ g kg}^{-1} \text{ day}^{-1}$) than at 10 cm depth. By the time sampling ended at DOY 314 (10 November), soil water concentrations were 90, 60, and 51 % of that at the beginning of sampling at 10, 35, and 70 cm depths, respectively, showing that soil water concentration was relatively slow to recover at depth compared to that near the soil surface. Depletion of soil water concentrations across the growing season was similar to that of a nearby pecan alley cropping practice on an upland site, where tree growth was adversely affected by soil water stress (Brauer et al. 2004). The fact that these black walnut trees did not exhibit soil water stress, i.e., premature leaf drop, like pecan or black

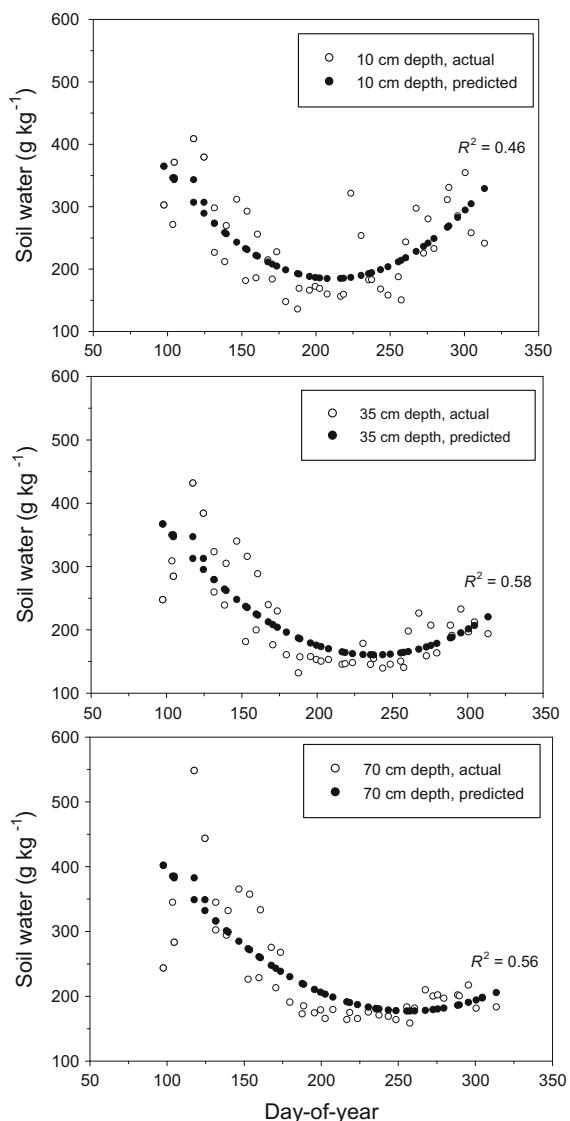


Fig. 2 Soil water depletion responses at 10, 35, and 70 cm depths under black walnut trees near Booneville, Arkansas

walnut on upland sites (Brauer et al. 2004) demonstrated the potential importance and seasonal dynamics of soil water stored at depth for growth of deep-rooted trees like black walnut (Garrett and McGraw 2000).

Herbage yields and foliar analyses

Herbage yield was significantly ($P < 0.001$) affected by N-rate, with the 100 kg ha^{-1} N-rate yielding more ($5,100 \text{ kg ha}^{-1}$) than the 0 kg ha^{-1} N-rate

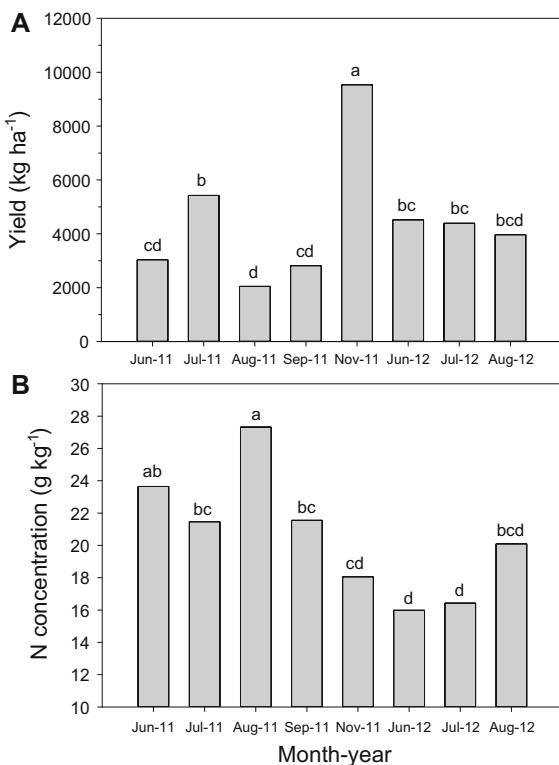


Fig. 3 Yield (a) and N concentration (b) of understory herbage in 2011–2012 near Booneville, Arkansas

(3,800 kg ha⁻¹). There was a significant year by date within year interaction for yield of understory herbage. Yields in June–August 2011 generally did not differ significantly from corresponding months in 2012 (Fig. 3a). Herbage yield in November 2011 was significantly greater than at other harvest dates (Fig. 3a), perhaps because of rainfall during August–October 2011 (Fig. 1) or because of the decreased herbage yield in tree shade (June–September) compared that without shade in November (Burner and MacKown 2005).

There was a significant year by date within year interaction for understory herbage N concentration. Herbage N concentration tended to be high in August each year (Fig. 3b). The low herbage N concentration in November 2011 probably was associated with corresponding high herbage yield (Fig. 3a). Tree shade tends to increase herbage N concentration, particularly NO₃-N concentration, compared to unshaded environments (Burner 2003; Burner and MacKown 2006). This could explain some of the high,

early-season herbage N concentrations for June and August 2011 (Fig. 3b).

Tree foliar N had a significant type by herbage suppression interaction. Wild-type black walnut in the herbicide spray treatment had significantly greater foliar N (30.5 g kg⁻¹) than that of variety in the control treatment (28.4 g kg⁻¹), or wild-type in the mow treatment (28.4 g kg⁻¹). The other types by herbage suppression treatments were intermediate (29.2–29.5 g kg⁻¹). Regardless of treatment, foliar N exceeded that considered adequate (≥ 26.0 g kg⁻¹ N, Schlesinger and Funk 1977), and was at or above previously reported values (16.0–22.5 g kg⁻¹ N) in Indiana (Andersen et al. 1989). Black walnut seedlings have significantly greater foliar N with N fertilization (Nicodemus et al. 2008). For older trees, lack of a foliar response to fertilizer N during a 2-year study was expected because at least 50 % of total leaf N of hardwood species is provided from the large pool of N stored in perennial tissues the previous year, and remobilized within 3 mo of budburst (Frak et al. 2005; Millard 1996). Thus, there might have been a foliar response to fertilizer N if sampling had occurred later in the growing season or been conducted for more years. Failure to detect a response to N-rate also might have been due to adequate soil mineral N (not determined).

Foliar P had a significant type by N-rate interaction. Variety (1.44 g kg⁻¹ P) and wild-type (1.43 g kg⁻¹ P) in 100 and 0 kg ha⁻¹ N treatments, respectively, had significantly more foliar P than wild-type that received 100 kg ha⁻¹ N (1.30 g kg⁻¹ P), while variety receiving the 0 kg ha⁻¹ N treatment was intermediate (1.41 g kg⁻¹ P). Foliar P concentrations were lower than reported (2.2–3.3 g kg⁻¹ P) in Indiana (Andersen et al. 1989), and were below the optimum concentration of ≥ 2.5 g kg⁻¹ P (Schlesinger and Funk 1977). Since soil P concentration was not adequate, as initially thought, trees might have responded to P fertilization.

Tree growth and phenology

There were no significant ($P \geq 0.07$) main effects or interactions for dbh and height, except for a year effect on dbh. Tree dbh increased ($P \leq 0.001$) from 15.8 (2011) to 17.0 cm (2012), but the annual change in tree height (8.8 m in 2011 and 8.9 m in 2012) was not significant ($P = 0.25$). Plant type did not affect dbh or

height in a survey of existing stands (Ares and Brauer 2004). Tree dbh and height were consistent with those on highly productive sites (Ares and Brauer 2004), and were projected to be about 17 m-tall at 65-year-old (Schlesinger and Funk 1977). Black walnut seedlings should have a ≥ 1.2 m radius vegetation-free zone to maximize seedling height and basal diameter (Hou et al. 2013), which had been maintained from post-planting until at least 2007. Thus, lack of a dbh response to herbage suppression or N fertilization might have been due to the long-term establishment of a vegetative free zone at planting which optimized seedling establishment and growth, a deep, alluvial soil that may have had an adequate soil N concentration (not tested), and too short a time frame for N fertilization to elicit dbh and height growth responses in pole-sized trees (Burner et al. 2010; Michalek 2003).

Date of budburst had a significant N-rate by herbage suppression interaction. Budburst was significantly earlier in the herbage control treatment with 0 kg ha⁻¹ N (DOY 102) than 100 kg ha⁻¹ N (DOY 107), with other N-rate by herbage treatments being intermediate (DOY 104–106). The significantly greater herbage yield in the control treatment at 100 kg ha⁻¹ N than 0 kg ha⁻¹ N ($P < 0.001$) probably caused the nearly 4.5 days delay in budburst. Thus, N fertilizer should be applied in conjunction with understory herbage suppression to avoid delay of budburst.

Date of budburst was comparable to that of pecan (DOY range 92–107) but later than white oak (DOY range 90–101) from a nearby upland site (Burner et al. 2014). Black walnut varieties spanned a 23 days interval for mean date of budburst (12 April, DOY 103, to 5 May, DOY 126) in central Missouri, latitude 39.02N (Warmund and Coggeshall 2010). Budburst occurred unusually early (DOY 90–97) for black walnut in Illinois, rendering it very susceptible to freeze damage (Augspurger 2009). Timing of budburst varies across latitudinal gradients as a function of long-term accumulation of forcing and chilling units (Harrington et al. 2010; Lechowicz 1984), probably accounting for the tendency for earlier budburst in this study compared to that in Missouri.

There was a significant type by DOY interaction for radial stem growth. For any given DOY, there was only one significant difference between types (DOY 160), when growth rate of the wild-type

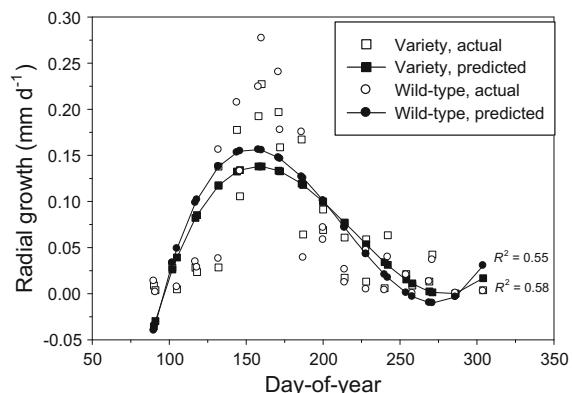


Fig. 4 Phenology of radial stem growth of black walnut types near Booneville, Arkansas

(0.28 mm day⁻¹) was greater than that of the variety (0.23 mm day⁻¹). The wild-type had a more rapid early-season growth rate than the variety, up to about DOY 200, after which the variety had more rapid growth rate (Fig. 4). Maximum predicted radial stem growth occurred on DOY 158 regardless of type. Averaged across types, rate of radial stem growth generally increased during the initial 60-day measurement period (early April, DOY 90, to late May, DOY 150), following which growth rate decreased during the next 150 days. Radial stem growth approached zero about DOY 275 (late October), but there was a slight increase in growth rate until measurements ceased.

Radial stem growth typically exhibits a cubic temporal response resulting from tissue dehydration associated with decreased soil water availability (Monk 1959). Tissue dehydration after mid-summer is a normal physiological process associated with development of frost hardiness (Monk 1959). Our results support the finding that radial stem growth of black walnut begins at or about budburst, or soon after full leaf expansion (Gould et al. 2011a; Walker and Oswald 2000).

We observed that black walnut on an adjacent upland site often partially or wholly senesces during hot, dry periods in late summer, and then refoliates after rainfall occurred in the fall. Premature leaf drop is associated with cessation of radial stem growth. This observation is consistent with the finding that the photosynthetic apparatus of black walnut is especially prone to drought stress, compromising its ability to thrive on xeric sites (Ni and Pallardy 1991; Parker and Pallardy 1991). The

transient increase in late-season radial stem growth could reflect an adaptive response to cooler air temperatures and an increase in soil water prior to cessation of growth (Fig. 1), although irrigation does not extend the period of stem circumference growth of mature black walnut in Missouri (Lucier and Hinckley 1982).

There was a significant year by method (dbh by d-tape vs. stem diameter by band dendrometry) effect on stem diameter. Band dendrometry gave significantly greater annual stem diameter compared to the d-tape method in 2011 (14.9 vs. 11.5 cm, respectively) and 2012 (13.1 vs. 11.2 cm, respectively). This overestimation supported previous findings (Burner et al. 2014; Day and Monk 1977; Zimmermann and Brown 1971). The physiological basis for this discrepancy is attributed to disparity between the relative rates of stem hydration-dehydration in spring and fall versus cambial growth (Monk 1959). Our data suggested there was greater relative stem rehydration to cambial growth in both years. Experimental error in radial stem measurements per se, or measuring dbh and radial stem growth at different positions on the tree stem, also could contribute to the discrepancy. Failure of newly-installed replacement bands to be properly seated on the stem also can cause measurement error, but this source of error was unlikely because a loose band causes radial stem growth to be underestimated (Keeland and Young 2012). Regardless, the discrepancy does not negate the value of periodic radial stem growth measurements for interspecific comparisons unless comparing growth rates with and without cell division (Monk 1959).

There was a significant three-way interaction of type, N-rate, and herbage suppression on LAI. Both types responded significantly to N-rate in the herbage control treatment (no suppression), with LAI being consistently lower at 100 than 0 kg ha⁻¹ N (Fig. 5). However, types did not respond significantly to N-rate in either the mow or herbicide herbage suppression treatment ($P \geq 0.83$). There was a tendency for LAI of the wild-type to be reduced with N fertilization in mow and herbicide treatments, but differences were not significant ($P \geq 0.14$). There was a significant main effect of DOY on LAI, and no other interactions with DOY were significant ($P \geq 0.79$). Regression responses showed the wild-type had a consistently greater LAI than the variety at any given DOY (Fig. 6).

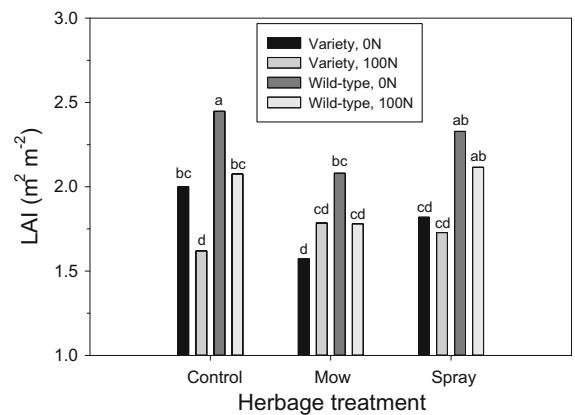


Fig. 5 Effect of N fertilization and herbage suppression on leaf area index (LAI) of black walnut types near Booneville, Arkansas

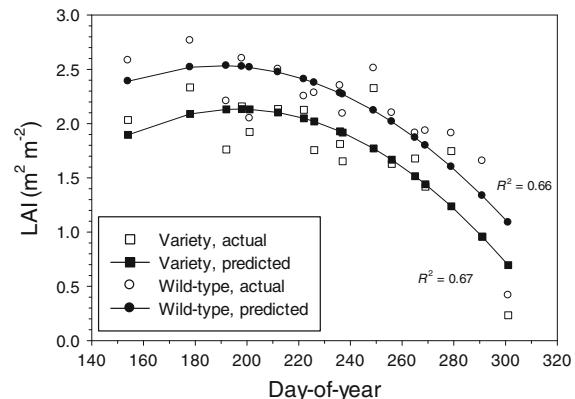


Fig. 6 Phenology of leaf area index (LAI) of black walnut types (variety and wild-type) near Booneville, Arkansas

There was a type by DOY interaction for maximum quantum yield of photosystem II (Fv/Fm), but N-rate, herbage suppression, and their interactions were not significant ($P \geq 0.07$). Types had similar DOY regression responses (Fig. 7) and did not differ significantly ($P \geq 0.99$) in Fv/Fm until DOY 299 (late October), when the wild-type had a significantly greater leaf fluorescence than the variety (Fv/Fm = 0.53 and 0.33, respectively). Within types, there were significant decreases in mean Fv/Fm across DOY. For the variety, mean Fv/Fm at DOY 299 (0.33) was significantly less than at DOY 159 (0.86). Similarly, the wild-type decreased significantly from 0.87 at DOY 159 to 0.75 (DOY 292) and 0.53 (DOY 299). Thus, there were negligible differences between

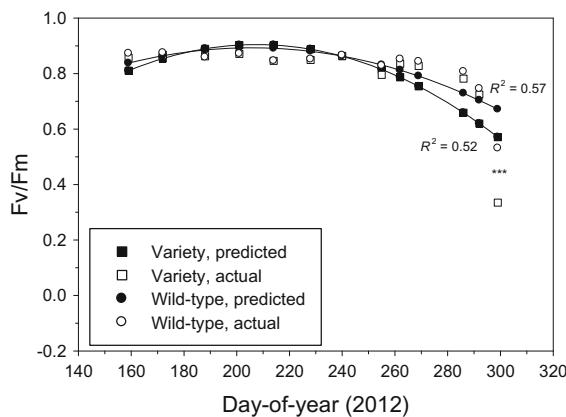


Fig. 7 Phenology of maximum quantum yield of photosystem II (F_v/F_m) for black walnut types near Booneville, Arkansas. Asterisks indicate day-of-year when means differed significantly (**indicate $P \leq 0.001$ level)

types until at or near the end of the growing season when the variety had lower photochemical efficiency of PSII than the wild-type. Within-season F_v/F_m of about 0.83 indicate that tissues were healthy during that time, while its late-season decrease could indicate presence of a range of stressors such as cold temperature, leaf age, or drought (Mohammed et al. 2003).

There was a significant type by DOY interaction for total chlorophyll concentration. The type by DOY interaction was attributed to different regression responses, as total chlorophyll decreased linearly and quadratically for the variety and wild-type, respectively (Fig. 8). There were, however, no significant differences between type means on any given DOY ($P \geq 0.41$). There also was a significant type by N-rate by herbage suppression interaction, but means did not differ in a consistent manner (data not shown). A well-established consequence of leaf senescence is chlorophyll degradation into photosynthetically-inactive catabolites (Matile et al. 1996), which likely accounts for the late-season decrease in F_v/F_m (Fig. 7) when chlorophyll content was at its lowest. However, this did not adequately explain full-season responses of F_v/F_m because chlorophyll concentration decreased rapidly throughout the measurement period, unlike F_v/F_m . Typically, PSII efficiency is unaffected over a broad range of chlorophyll concentrations and will maintain high F_v/F_m values until chlorophyll content is extremely low during senescence (Adams et al. 1990). It is important to note that drought and high temperature have also been shown to substantially

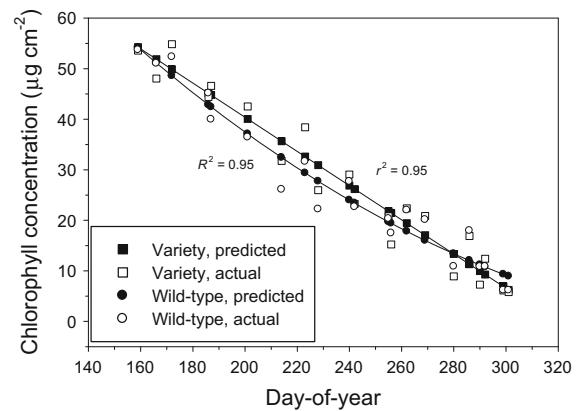


Fig. 8 Phenology of total chlorophyll concentration for black walnut types near Booneville, Arkansas

decrease leaf chlorophyll content without concomitant declines in F_v/F_m (Haldimann et al. 2008). Air temperature (Fig. 1), soil moisture (Fig. 2), and stem growth data (Fig. 4) indicate above-average temperatures, increasingly dry soil, and declines in stem growth (an indicator of drought stress; Jones 2004) concomitant with declines in chlorophyll concentration. These findings suggest that the decline in chlorophyll content prior to leaf senescence at the end of the season was likely due to abiotic stress conditions during the measurement period.

In summary, our results showed that foliar and stem phenology was affected more by plant type than by herbage treatment. Nitrogen fertilization delayed budburst in the herbage control treatment by increasing herbage yield. Early-season radial stem growth was greater for the wild-type than the variety, after which the variety had more rapid growth. Radial stem growth virtually ceased in late October, about 30 days before termination of LAI, leaf fluorescence, and leaf chlorophyll samplings, i.e., leaf drop. The wild-type had consistently greater LAI than the variety at any given DOY, and usually had greater LAI than the variety across herbage treatment. Leaves of both plant types maintained a high level of primary photochemical efficiency across most of the growing season. Plant types diverged relatively late in the growing season, with the variety having lower maximum quantum yield than the wild-type only at final sampling date. Unlike chlorophyll fluorescence, total chlorophyll concentration decreased across the growing season regardless of plant type.

Conclusions

The high valued products (nuts and timber) derived from black walnut prompt its serious consideration as a plantation species on suitable sites. Selection of appropriate plant type (variety vs. wild-type) is critical at the inception of a black walnut plantation to optimize profitability throughout the rotation. More information is needed to determine if plant type and understory management affects tree phenology. Herbage treatments might have had little impact on phenological responses because of the long-term maintenance of, 1) a vegetative free zone that optimized seedling establishment and early growth, 2) a deep, alluvial soil that might have had adequate soil N, and 3) too short a time frame for herbage treatments to have affected these pole-sized trees. Contrary to the initial soil P assessment, trees might have benefited from supplemental P fertilization. Differences in phenological responses between plant types might have been greater across latitudinal, soil fertility, or soil water gradients.

These results have implications for landowners wanting to develop walnut plantations as a long term source of farm income. One of the first decisions confronting a landowner is whether to plant either native or varietal trees. The results from this study indicated that overall tree growth was not significantly affected by tree type. Varietal seedlings, especially grafted stock, are considerably more expensive to purchase than native seedlings, providing an advantage to native tree type.

If the landowner is pursuing maximum returns, income from timber is more likely to boost life cycle returns (Ares and Brauer 2004). Under these circumstances native trees are more likely to produce more income from timber. Varietal trees tend to be more branched in their growth habit, thus requiring more management through pruning, etc. to produce a high quality timber trunk with acceptable number and size of knots. Grafted varietal trees are very unlikely to produce an acceptable timber trunk because of discoloration and dark streaking originating from the graft region (HG Garrett, personal communications). The planting of native trees may not provide the opportunity to sell nuts of higher quality at a premium price; however, to take advantage of this premium, the grower needs to be located near a purchasing agent that is able to accept high quality nuts. Such purchasing agents are not widely distributed in the eastern

U.S. It is possible that native trees can produce higher quality nuts that may warrant a premium price; Brauer (unpublished data from 2004 to 2007) observed nut meat yields of 20–24 % from native trees that were well managed, i.e., little water stress, optimum fertilization and pruning as compared to the 10 % typically reported for native trees.

There were only small differences in tree growth attributed to the three understory management scenarios. This is in contrast to seedling trees first few years after transplant in which tree growth responded positively to less understory competition in immediate proximity to the tree trunk (Brauer and Jones 2003; Brauer and Idassi 2005; Brauer et al. 2010). Newly transplanted trees have restricted root zone and competition within this zone may have detectable effects on tree growth. As trees grow and occupy the site, the soil volume in contact with the trees' root systems increases immensely. Brauer et al. (2010) observed significant concentrations of tree roots in the top 1 m of soil at mid-point of the tree rows at this site, when excavating soil cores. The ability of the walnut trees to extract nutrients and water from a large surface area overlying a deep soil may counteract the competition between the understory and the walnut trees. If no benefit to tree growth is being derived from understory control by either mowing or herbicide applications, elimination of these activities will increase the profitability of the system by decreasing input costs. Future research is needed to better understand the point in which understory management changes from being beneficial to tree growth to being of little significance.

If a landowner is interested in alley cropping, i.e. producing forage from the alleys between tree rows, results from this study provide insight into the optimal management practices. First of all the area covered with understory should be maximized, thus herbicide application within the area adjoining the tree trunk should not be made. Second, the understory should receive ample N fertilization to support maximum forage production.

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